Radio Science, Volume ???, Number , Pages 1–23,

Reducing the Power Consumption in LTE-Advanced Wireless Access Networks by a Capacity Based Deployment Tool

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As both the bit rate required by applications on mobile devices and the number of those mobile devices are steadily growing, wireless access networks need to be expanded. As wireless networks also consume a lot of energy, it is important to develop energy-efficient wireless access networks in the near future. In this study, a capacity-based deployment tool for the design of energy-efficient wireless access networks is proposed. Capacity-based means that the network responds to the instantaneous bit rate requirements of the users active in the selected area. To the best of our knowledge, such a deployment tool for energy-efficient wireless access networks has never been presented before. This deployment tool is applied to a realistic case in Ghent, Belgium to investigate three main functionalities incorporated in LTE-Advanced: carrier aggregation, heterogeneous deployments, and Multiple-Input Multiple-Output (MIMO). The results show that it is recommended to introduce femtocell base stations, supporting both MIMO and carrier aggregation, into the network (heterogeneous deployment) to reduce the network's power consumption. For the selected area and the assumptions made, this results in a power consumption reduction up to 70%. Introducing femtocell BSs without MIMO and carrier aggregation can already result in a significant power consumption reduction of 38%.

1. Introduction

The number of mobile devices such as tablet PCs (Personal Computers), laptops, and smartphones clearly gives a boost to the growth of wireless access networks. Not only the number of devices has its influence on the traffic load on wireless access networks, but also the type of applications running on these devices. Streaming music and video, making video calls, visiting social network sites on the go, etc. require higher bit rates than an ordinary phone call. The use of these high-bandwidth applications results in the expansion of today's wireless access networks [*Cisco*, 2012]. However, wireless access networks, and more specifically the Base Stations (BSs) of these networks, currently already consume a large amount of power [*Deruyck et al.*, 2012a]. Therefore, it is important to develop energy-efficient wireless access networks in the near future [*Deruyck et al.*, 2012a; *Marsan et al.*, 2010; *Koutitas*, 2010].

In this paper, a deployment tool is proposed for the design of future energy-efficient wireless access networks that will respond to the instantaneous bit rate required by the users active in the considered area. Therefore, 3D geometrical data of the environment is taken into account. New techniques such as a combination of femtocell and macrocell base stations are applied in this tool. To the best of our knowledge, such a deployment tool for wireless access networks has never been presented before. In [*Marsan et al.*, 2010; *Couta da Silvia et al.*, 2012], a similar approach is investigated but only for dense WLANs (Wireless Local Area Networks). Based on this deployment tool, three main features incorporated in LTE-A (Long Term Evolution-Advanced) are investigated: carrier aggregation (CA) whereby the bit rate is increased by letting the base station transmit at multiple carriers up to a total bandwidth of 20 MHz to the users, heterogeneous networks whereby macrocell and femtocell base stations can be mixed in one network, and MIMO (Multiple-Input Multiple-Ouput) which in this case will be used to enhance the coverage of the base station by using multiple antennas on one base station (spatial diversity). In [*Deruyck et al.*, 2013] only one single base station was investigated, while in this investigation the influence on the power consumption and energy efficiency of the whole network is investigated. The deployment tool is applied for a dynamic LTE-Advanced deployment at 2.6 GHz in a suburban area in Ghent, Belgium.

The outline of this paper is as follows: Section 2 discusses the deployment tool. In Section 3 the energy efficiency metric is defined and Section 4 presents the results obtained with the deployment for the three features incorporated in LTE-Advanced.

2. Design tool for energy-efficient wireless access networks based on required capacity

As mentioned above, the developed tool will respond to the actual requests of users for a certain bit rate. In the first phase, realistic traffic will be generated. In the second phase, the actual network will be developed.

2.1. Phase 1: generating traffic

As traffic usually varies during the day, traffic will be simulated for different time intervals. For each time interval, the maximum number of simultaneous active users is determined, along with the location of each user and his or her requested bit rate.

This data is collected in a file for each time interval. To provide this data, a number of distribibition functions are combined as shown in Fig. 1:

- *User distribution*: the user distribution determines the maximum number of users that are simultaneously active for a certain time interval. This depends of course on the population density of the considered area as shown in Fig. 1. The bar graph in Fig. 2 shows the evolution of the maximum number of simultaneous active users during the day. These data is obtained from processing measurements [*Deruyck et al.*, 2012b]. [*Joseph et al.*, 2010] and [*Gati et al.*, 2009] confirm these results.
- *Location distribution*: the location distribution determines for each user individually the location of the user within the considered area.
- *Bit rate distribution*: the bit rate distribution determines for each user individually the bit rate that the user requests. For a certain time stamp, a part of the users are making a voice call requesting 64 kbps and the other part of the users are transferring data requesting 1 Mbps. The voice users are indicated in dark blue in Fig. 2, while the data users are indicated in light blue.

The information saved in the traffic file(s) is then used in the next phase to create an energy-efficient network. Due to the distributions described above, multiple simulations need to be executed for each time interval. To determine how many simulations are needed, we performed up to 70 simulations and determined the estimated mean of the power consumption as a function of the number of simulations. Based on this function, we determined how at least necessary to obtain a good estimation of the mean. A number of 40 simulations was obtained. For each time interval, 40 traffic files will thus be generated and the median value is considered [*Kutner et al.*, 2005]. For each traffic file, a network topology will be created.

2.2. Phase 2: creating the network

Once the traffic files are composed (phase 1 of the algorithm), a network can be created for each time interval and each traffic file following the procedure shown in Fig. 3. In addition to the traffic files, a file providing information with the locations of the BSs is also needed, together with a shape file providing information about the environment and buildings of the considered area. For each time interval and each traffic file (Steps 1 and 2 in Fig. 3), a network will be designed. In the end, we will have 960 networks (= 24 time intervals and 40 simulation cases per time interval). The algorithm tries to cover each user for the considered time interval and simulation case (Step 3). The next steps will thus be repeated up to maximum m times with m = the maximum number of simultaneous active users for that time interval. First, it is checked if the user can be served by a BS that is already enabled (Step 4) as it is the most energy-efficient to connect users to existing BSs instead of enabling new BSs to the network. The user will be connected to the BS from which the user experiences the lowest path loss (which has to be lower than the maximum allowable path loss to which a transmitted signal can be subjected while still having a sufficient quality at the receiver side to offer the bit rate requested by the user. To determine the path loss, the straight line between the user and the BS is determined. The information provided in the shape file with the 3D data about the environment tells if there is any building obstructing this line. If so, the Walfish-Ikegami (WI) non-Line-of-Sight (nLoS) model is used, otherwise the WI Line-of-Sight (LoS) model [*COST Action 231*, 1999] is applied. Furthermore, each user is assigned a certain shadowing margin by using a normal distribution with σ equal to the standard deviation of the used propagation model. If it is not possible to connect the user with an already enabled BS, the algorithm will check if it is possible to connect the user by enabling a disabled BS (Step 5). The following condition needs to be fulfilled, just as connecting with an already enabled BS: the path loss experienced by the user needs to be lower than the maximum allowable path loss to offer the bit rate requested by the user and as low as possible. All disabled BSs will be investigated and if a BS is found so that the condition above is satisfied, this BS will be enabled. Note that also the input power of the BS (which directly influences the power consumption of the BS) and the modulation scheme are tuned to cover the highest possible number of users with a minimal power consumption [*Deruyck et al.*, 2010]. Furthermore, the algorithm will check if users already connected by other BSs can be transferred to this BS (Step 6), because they might experience a lower path loss from this BS. If this is the case, it is checked whether the input power of the BS from which the user is removed can be reduced.

If no BS can be enabled or all BSs are already enabled, the user can not be served.

3. Energy efficiency of the wireless access network

First, the absolute power consumption value will be calculated to compare the proposed networks. Second, to make a fair comparison of the performance of the different networks, the energy efficiency is defined as follows (in (km$^2\cdot$ Mbps)/W) [*Deruyck et al.*, 2013]:

$$EE = \frac{A \cdot U \cdot \sum_{i=1}^{n} B_i}{\sum_{i=1}^{n} P_i} \tag{1}$$

with A the area covered by the network (in km^2), U the number of served users, n the number of the base stations in the network, B_i the bit rate of base station i (in Mbps), and P_i the power consumption of base station i (in W). The energy efficiency metric takes the most important performance metrics into account. Here, the covered geometrical area, the number of served users, the bit rate offered by the network, and, of course, the power consumption is taken into account. The capacity offered by the network is considered instead of the bit rate required by the users as the capacity offered by the network can be equal or (slightly) higher than the sum of the bit rates required by the users. Furthermore, the capacity offered by the network is representative for the network, while the bit rate required by the users is representative for the user behavior rather than for the network. The metric defined here is a combination of three already existing energy efficiency metrics which define the energy efficiency as the covered geometrical area when consuming 1 W power $\frac{A}{P_{el}}$ as defined in [*Correia et al.*, 2010], the number of served users when consuming 1 W power $\frac{U}{P_{el}}$ as proposed in [*Baliga et al.*, 2011; *Vereecken et al.*, 2011], and the bit rate offered when consuming 1 W power $\frac{B}{P_{el}}$ as in [*Correia et al.*, 2010; *del Apio et al.*, 2011]. Note that other algebraic compositions are possible to combine these metrics into one metric than the one proposed in Eq. (1). Another composition will result of course in other absolute values. However, the purpose of the metric in this paper is to define which scenario performs the best. Which algebraic composition is used is thus of minor importance as long as the relative results remain the same. Furthermore, each parameter in the metric is here of equal importance in order to make a fair comparison between the different scenarios. If a higher importance is allocated to one parameter, scenarios that influence that parameter will be advantaged.

The higher EE, the better the network performs in terms of energy efficiency. When a higher coverage and/or higher capacity and/or higher number of covered users is obtained by the network for the same power consumption, the nominator of Eq. (1) will become higher which will result in a higher value for the energy efficiency metric compared to the network that offers a lower coverage and/or lower capacity and/or a lower number of covered users for the same power consumption.

4. Results

4.1. Selected area and simultaneous active users

For this study, an outdoor suburban area of 6.85 km^2 in Ghent, Belgium is selected which is shown in Fig. 4. The possible locations (75 locations) for the base stations are indicated by red squares and are existing locations from Belgian mobile operators. The users are uniformly spread over the area of interest which results in equidistant discrete samples in both x and y direction. Note, that for another area e.g., an area with a mixture of suburban and rural parts, a different approach could be used as the user density in the suburban part will be higher than in the rural part.

The maximum number of simultaneous active (voice and data) users per hour over one day in the considered area is shown in Fig. 2. Note that for all simulations for a certain time interval and for each scenario, the number of simultaneous active voice and data users will be the same. Although these users are uniformly distributed over the considered area, the requested bit rate at each location will vary from simulation to simulation, depending on which type of user (voice or data) is located on that location. Due to this fact, 40 simulations are necessary to obtain a good estimation of the expected value of the different parameters as mentioned above. Note that this number of simulations only applies to the selected scenario. For a different scenario (for e.g. with three different bit rates), more simulations will need to be performed.

4.2. Assumptions

Table 1 gives an overview of the chosen value for the different parameters of the LTE-Advanded link budget. We consider an LTE-Advanced network at 2.6 GHz. When applying MIMO, an additional gain, the MIMO gain, is taken into account and is calculated as follows:

$$G = 10 \cdot log(N_{Tx} \cdot N_{Rx}) \tag{2}$$

with N_{Tx} the number of transmitting antennas and N_{Rx} the number of receiving antennas. Note that this MIMO gain corresponds with the theoretical MIMO gain which might be an overestimation for some realistic cases. To determine the power consumption (PC) of a base station, the power consumption model of [*Deruyck et al.*, 2012a] is used.

4.3. Reference scenario

The reference scenario used in this study is the scenario whereby the developed networks consist of only macrocell base stations not supporting carrier aggregation nor MIMO. All the results will be presented as the 50^{th} and 95^{th} percentile calculated over the 40 simulations. As the network responds to the instantaneous bit rate requirements of the users active in the area, the number of selected base stations in the network will vary during the day, resulting in a varying power consumption, and thus energy efficiency, of the network. Fig. 5 shows the evolution of both the power consumption (left blue axis) and the energy efficiency (right red axis) during the day for both the 50th and the 95th percentile. The power consumption is the highest during daytime (from 10 a.m. till 8 p.m.). The energy efficiency reaches its highest level around 5 p.m. when the highest number of users is active in the network. On the other hand, the energy efficiency is the lowest around 3 a.m. to 4 a.m. when the lowest number of users is active in the network. Although the power consumption is higher around 5 p.m. than around 3 a.m. to 4 a.m., a higher energy efficiency is obtained due to better performance of the network (higher offered capacity, higher number of users served, and a higher coverage). Fig. 6 shows the network obtained from one simulation case for four different time intervals during the day. The red squares indicate the location of the base stations, while the blue triangles indicate the location of the users. For the networks at 12 a.m. and 6 p.m., of course much more active BSs are required than at 12 p.m. and 6 a.m. because of the higher number of active users (Fig. 6). Note that for each time interval, 40 simulations will be performed and thus 40 networks will be designed for each time interval. From now on, only two time intervals will be considered: the 4-5 a.m. time interval with the lowest number of active users (i.e, 14 users) and the 5-6 p.m. time interval with the highest number of active users (i.e., 224 users). The results will be presented as the 50^{th} (p_{50}) and 95^{th} (p_{95}) percentile calculated over the 40 simulation cases for each time interval. For each considered time interval, the standard deviation σ_{PC} and σEE and the confidence intervals CI_{PC} and CI_{EE} of the power consumption, respectively the energy efficiency, calculated over the 40 simulations is given. σ_{PC} is between 0.5 kW and 4.2 kW for the 4-5 a.m. time interval and between 1.4 kW and 6.1 kW for the 5-6 p.m. time interval which amounts to approximately 10% of the obtained p_{50} value due to the considered distributions (user, location, and bit rate distribution). Furthermore, the power consumption reduction and the energy efficiency improvement compared to the reference scenario will be determined for each scenario.

4.4. Carrier aggregation (CA)

Tables 2 and 3 show the results for both the power consumption (PC) and the energy efficiency (EE) for the two selected time intervals i.e., 4 a.m. to 5 a.m. (lowest number of active users) and 5 p.m. to 6 p.m. (highest number of active users), respectively when applying carrier aggregation compared to the reference scenario. 2 up to 5 carriers of 5 MHz are aggregated in this comparison and only macrocell

BSs are considered. When carrier aggregation is applied, multiple carriers are sent to the user to increase the bandwidth and thus the bit rate [*Dahlman et al.*, 2011]. However, possible drawbacks of carrier aggregation are: the vulnerability to loss in the throughput, interference coordination, the incompatibility with user equipment, etc.

The impact of introducing carrier aggregation on the BS's power consumption is negligible as it corresponds in practice to a multicarrier (not aggregated) configuration that is already supported by LTE or to a base station supporting multiple frequency bands [*Dahlman et al.*, 2011]. Figs. 7 and 8 give an overview of the individual parameters (number of active base stations (a), network power consumption (b), number of users served by the network (c), and the capacity offered by the network (d)) for the two selected time intervals. As CI_{EE} do not overlap, it is concluded that the more carriers are aggregated, the more energy-efficient the solution becomes. Aggregating 5 carriers results for the considered case in an EE improvement of 400% (Tables 2 and 3, for both p_{50} and p_{95}) due to the fact that a higher number of aggregated carriers results in a higher offered bit rate per BS for the same BS power consumption (CI_{PC} is approximately the same for the considered CAs) and thus in a higher network capacity (Figs. 7 (d) and 8 (d)). When aggregating two 5 MHz carriers, the capacity offered by the network multiplies by approximately 2, analogously when aggregation 5 carriers the capacity offered by the network multiplies by approximately 5. For all considered scenarios, all users active in the selected area are covered for the 4-5 a.m. time interval and 97% for the 5-6 p.m. time interval (Figs. 7 (a) and 8 (a)). For the 5-6 p.m. time interval, 3% of the users can not be covered, because the locations where new base stations can be illuminated are limited, and the path loss experienced by the user from base stations on these locations is not lower than the maximum allowable path loss (Section 2).

For the selected area, carrier aggregation does not result in a lower power consumption. The same number of base stations (13 for 4-5 a.m. (Fig. 7 (a) and 27 for 5-6 p.m. (Fig. 8 (a)) is used for the different scenarios where CA is applied as for the reference scenario because the capacity per BS is not the most limiting factor to develop the network but the range per BS.

4.5. MIMO

The second feature that is investigated is MIMO. Tables 2 and 3 also list the values for the power consumption and the energy efficiency compared to the reference scenario for the 4-5 a.m. and the 5-6 p.m. time interval respectively. Three different cases are studied: SISO (Single-Input Single-Output) which corresponds with the reference scenario, 4x4 MIMO, and 8x8 MIMO. Spatial diversity is used, so a higher range will be obtained when applying MIMO. Figs. 7 and 8 give again an overview of the individual parameters for the two selected time intervals. The results for the EE parameter in Tables 2 and 3 show that for the selected area, MIMO does not lead to a higher EE.

For the 4-5 a.m. interval, EE is decreased with 17% to 22% when taking the p_{50} and p_{95} values into account compared to the reference scenario. However, CI_{EE} for the reference scenario and 4x4 MIMO overlay significantly. Therefore, it is concluded that the EE remains the same for this case. For the 5-6 p.m. interval, a decrease with 47% (p_{95}) to 49% (p_{50}) is obtained with non-overlaying CI_{EE} which means that the energy efficiency for this time interval is effectively decreased. For 8x8 MIMO, these reductions are even higher: 44% (p_{95}) to 51% (p_{50}) for the 4-5 a.m. interval and 67% (p_{50}) to 69% for the 5-6 p.m. interval. No overlap is found between the CI_{EE}, thus in general it is concluded that the energy efficiency for the considered case decreases when applying 8x8 MIMO. As applying MIMO results in a higher range per BS, fewer BSs are needed to cover all the users in the area (Figs. 7 (a & c) and 8 (a & c)) and thus less capacity is available in the network (Figs. 7 (d) and 8 (d)) resulting in a lower energy efficiency, despite the fact that the network consumes less power. When using 4x4 MIMO, the number of used BSs is reduced by 43% (p_{95}) to 54% (p_{50}) and 59% (p_{50}) to 61% (p_{95}) for the 4-5 a.m. and 5-6 p.m. interval respectively, resulting in approximately the same reduction in network capacity. When using 8x8 MIMO, the number of BSs is even further reduced compared to the reference scenario: by 57% (p_{95}) to 69% (p_{50}) and 64% (p_{95}) to 66% (p_{50}) for the 4-5 a.m. and 5-6 p.m. interval respectively, resulting also in approximately the same reduction in network capacity. The power consumption reduction for 4x4 MIMO amounts even up to 18% (p_{95}) for the 5-6 p.m. interval compared to the reference scenario (although the CI_{PC} slightly overlap) as fewer BSs are needed in the network (Figs. 7 (a) and 8 (a)). For 8x8 MIMO, there is no power consumption reduction although even fewer BSs are used (Figs. 7 (a) and 8) than for the 4x4 MIMO scenario. This is due to the fact that the extra power consumption needed to support the 8 antennas is too high. The

CI_{EE} for this case is also significantly higher than for the reference and 4x4 MIMO scenario.

Note that we assumed that the unselected BSs consume no power, so the considered case is an ideal situation. The obtained energy efficiency and power consumption gains are very dependent on the considered power consumption during sleep mode.

4.6. Heterogeneous deployments

In this section, the influence on the power consumption and energy efficiency of introducing femtocell BSs in the network is studied. The results for these parameters compared to the reference scenario are listed in Tables 2 and 3 for the 4-5 a.m. and the 5-6 p.m. time interval, respectively. Five different scenarios are investigated: (i) the network consisting of only macrocell BSs without CA and MIMO (i.e., the reference scenario), (ii) the combination of macrocell and femtocell BSs both not supporting CA and MIMO, (iii) the combination of macrocell and femtocell BSs where the femtocell BS supports 4x4 MIMO (spatial diversity), (iv) the combination of macrocell and femtocell BSs where the femtocell BS aggregates 5 carriers of 5 MHz, and (v) the combination of macrocell and femtocell BSs where the femtocell BS supports both CA and MIMO. Tables 2 and 3 show that introducing femtocell BSs in the network has a high influence on the energy effciency. When introducing femtocell BSs without CA and MIMO, an EE improvement of 66% (p_{95}) is obtained for the 4-5 a.m. interval and 149% (p_{50}) to 160% (p_{95}) for the 5-6 p.m. interval. This is due to the lower power consumption of the femtocell BS compared to the macrocell BS is significantly lower (12 W versus 1674 W) resulting in a network power consumption reduction (Tables 2 and 3, non-overlapping CI_{PC}) of 35% (p_{50}) to 38% (p_{95}) for the 4-5 a.m. time interval and 3% (p_{50}) to 7% (p_{95}) for the 5-6 p.m. time interval compared to the reference scenario, although a higher number of BSs is used (Figs. 7 (a) and 8 (a)). For the 5-6 p.m. time interval, the number of used BSs is increased by 123% (p_{95}) to 145% (p_{50}), while the number of used BSs is the same for the 4-5 a.m. time interval as for the reference scenario to cover the same number of users (i.e., 100% for the 4-5 a.m. interval and 97% for the 5-6 a.m. interval (Figs. 7 (a) and 8 (a)). Note, that collection of used BSs consists of both macrocell and femtocell BSs, while this collection consists only of macrocell BSs for the reference scenario. Furthermore, this large number of BSs also provides a higher network capacity thus resulting in a higher energy efficiency (non-overlapping CI_{EE}). For the 5-6 p.m. interval, the network capacity increases by 124% (p_{95}) to 146% (p_{50}) compared to the reference scenario. For the 4-5 a.m. interval, the increase is only 0.3% (for both p_{50} and p_{95}) compared to the reference scenario as the number of BSs is the same as for the reference scenario.

Comparing the scenario with MIMO and the scenario with CA shows that introducing femtocell BSs supporting MIMO influences the power consumption the most. CI_{PC} when using MIMO is significantly lower than when using CA. Furthermore, the CI_{PC} when using CA is similar to the CI_{PC} when using femtocell BSs without supporting MIMO or CA. A reduction of 68% (p_{50}) to 70% (p_{95}), respectively 17% (p_{50}) to 22% (p_{95}), is obtained for the scenario with femtocell BSs supporting MIMO for the 4-5 a.m., respectively the 5-6 p.m. time interval, versus 35% (p_{95}) to 38%

(p_{50}) respectively 4% (p_{50}) to 7% (p_{95}) for the scenario with femtocell BSs supporting CA (Tables 2 and 3). Due to MIMO, the range of the femtocell BSs is increased and more femtocell BSs (with a lower power consumption) than macrocell BSs are used although the total number of used BSs does not decrease (Figs. 7 (a) and 8 (a)). In contrary, introducing femtocell BSs supporting CA influences the energy efficiency most. An energy efficiency improvement of 760% (p_{50}) to 799% (p_{95}), respectively 133% (p_{50}) to 348% (p_{95}), is found for the 4-5 a.m. and 5-6 p.m. time interval versus 200% (p_{50}) to 221% (p_{95}) and 218% (p_{50}) to 309% (p_{95}) when introducing femtocell BSs supporting MIMO (Tables 2 and 3). The CI_{EE} differs significantly between the different scenarios. As CA increases the capacity per BS (Section 4.4), the overall capacity of the network increases, resulting in a high energy efficiency.

The best results are obtained when introducing both CA and MIMO. For this scenario, the consumed power is similar as for the scenario when supporting only MIMO as CI_{PC} overlaps significantly, but the energy efficiency improvement is much higher (CI_{EE} is significantly higher) when supporting both MIMO and CA (1123% for p_{50} to 1579% for p_{95}) as supporting CA results in a higher capacity per BS and MIMO in a higher range per BS.

In general, the highest gains (both power consumption (70% for p_{95}) and energy efficiency (1579% for p_{95})) are obtained for the time interval with the lowest number of active users.

5. Conclusion

A capacity based deployment tool for energy-efficient wireless access networks is proposed. The tool takes the instantaneous bit rate requirements of the user into account. Appropriate distributions are combined in order to simulate realistic traffic. Based on this tool, the influence on the power consumption and energy efficiency of three main functionalities (carrier aggregation, MIMO, and heterogeneous networks) of the LTE-Advanced standard are investigated for a realistic case in Ghent, Belgium. An appropriate power consumption model for LTE-Advanced macrocell and femtocell base stations is used as well as an appropriate energy efficiency metric to compare different scenarios. The highest power consumption reduction and energy efficiency improvement is obtained when applying the three features together i.e., a heterogeneous network whereby the femtocell base station supports both carrier aggregation (5 carriers of 5 MHz) and 4x4 MIMO. A power consumption reduction up to 70%, respectively 21%, is obtained for the time interval with the lowest, respectively highest, number of users compared to the macrocell only network without MIMO and carrier aggregation. Adding femtocell base stations without MIMO and carrier aggregation can already reduce the power consumption significantly: up to 38% (busiest time interval), respectively 7% (least busiest time interval), compared to the macrocell only network without MIMO and carrier aggregation. Furthermore, introducing femtocell base stations only supporting carrier aggregation has the highest influence on the energy efficiency, while introducing femtocell base stations only supporting MIMO has the highest influence on the power consumption.

Based on this study, it is recommended for future wireless access networks to take the advantage of the LTE-Advanced incorporated features, especially the introduction of femtocell base stations, to reduce the power consumption of the network.

Acknowledgments. The data used in this study is confidential data provided by third level parties. We conducted this work with the financial support of the iMinds project "Green Wireless Efficient City Access Networks" (GreenWeCan). E. Tanghe is a postdoctoral fellow of the Research Foundation Flanders (FWO-V).

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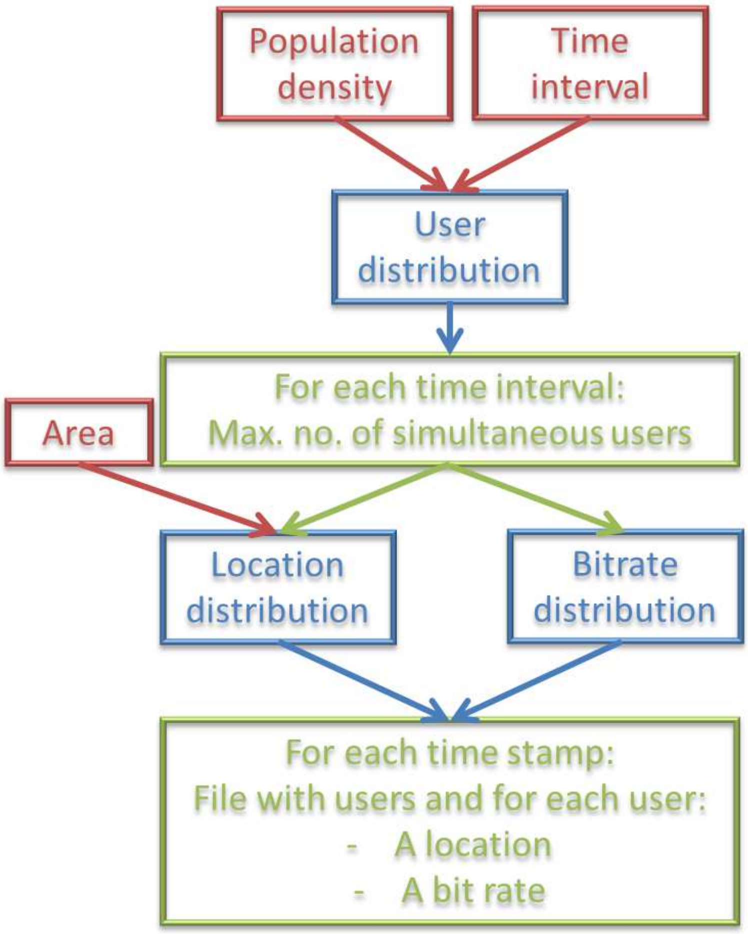

Figure 1. Flow diagram of phase 1 'generating traffic' of the capacity-based deployment tool for designing energy-efficient wireless access networks.

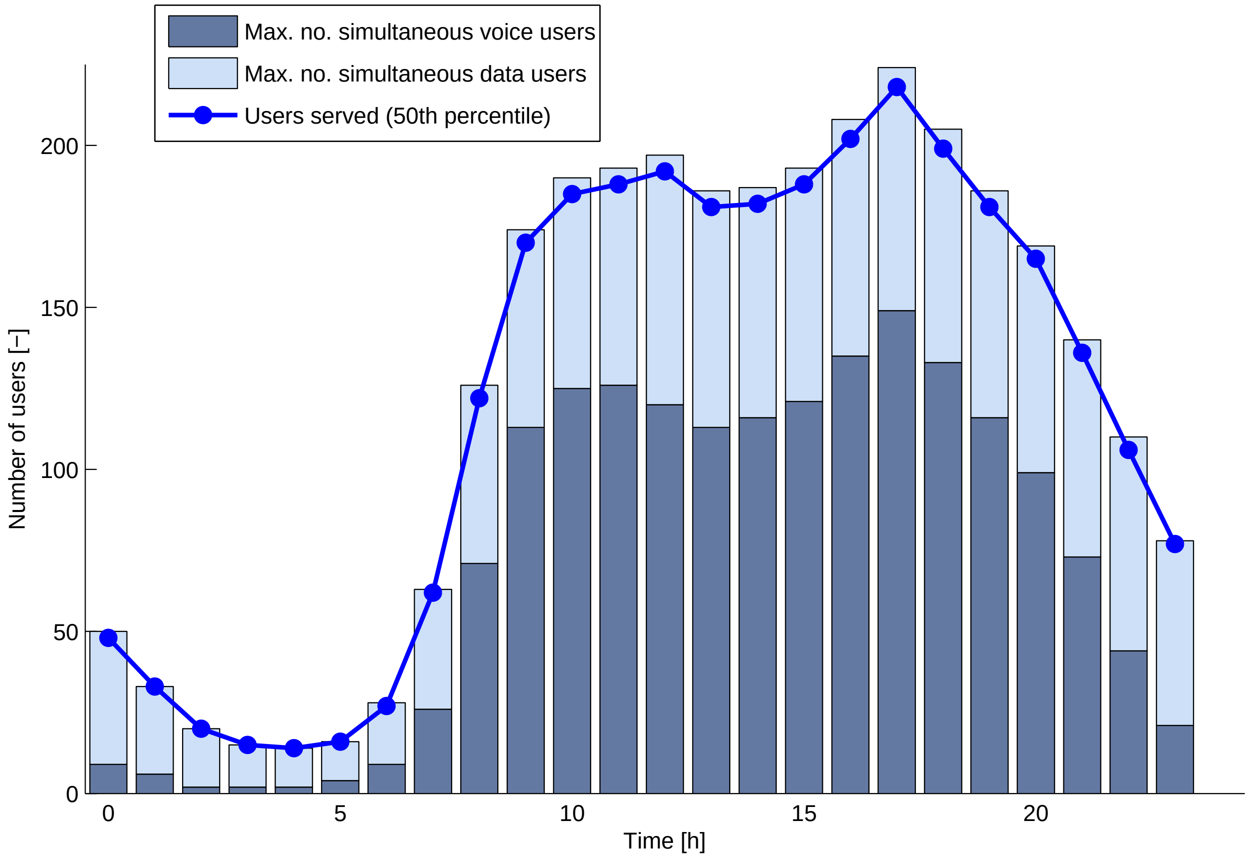

Figure 2. Maximum number of simultaneous active users during the day (bar graph) versus number of users served (50th percentile) by developed networks for the reference scenario.

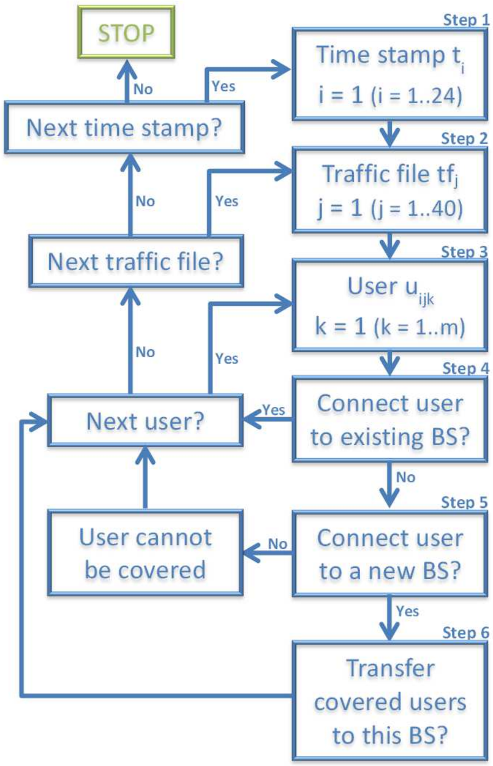

Figure 3. Flow-graph of phase 2 'creating the network' of the capacity based deployment tool for designing energy-efficient wireless access networks.

Figure 4. The selected suburban area of 6.85 km^2 in Ghent, Belgium.

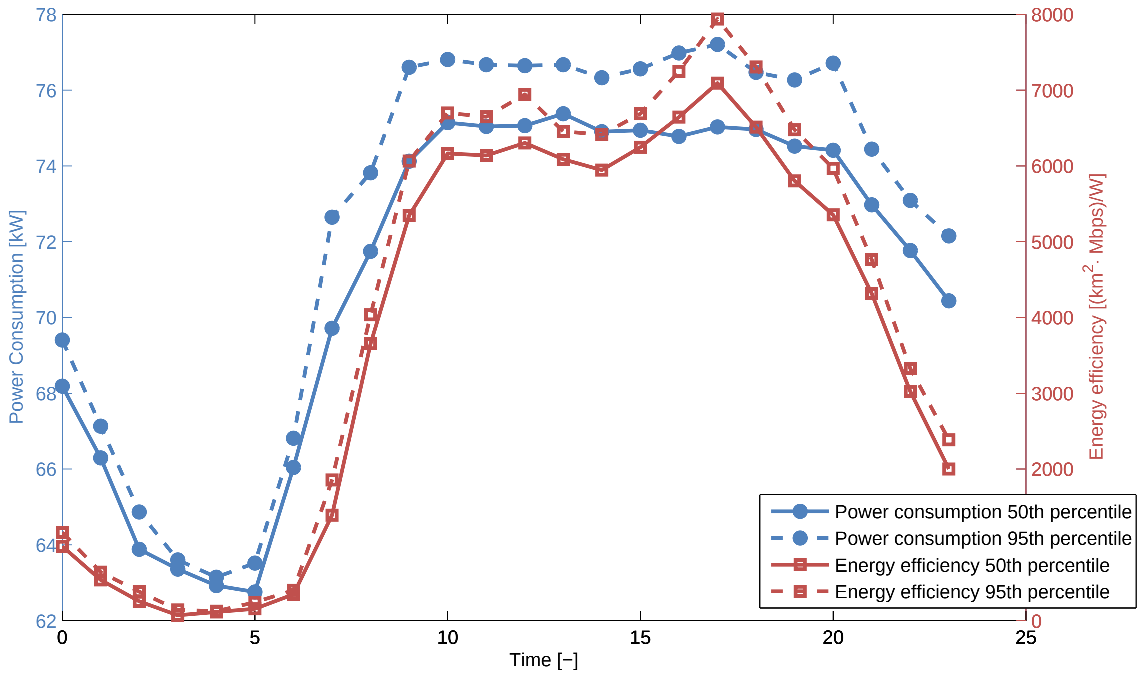

Figure 5. Evolution during the day of the 50th and 95th percentile of the power consumption (blue left axis) and energy efficiency (red right axis) for the reference scenario.

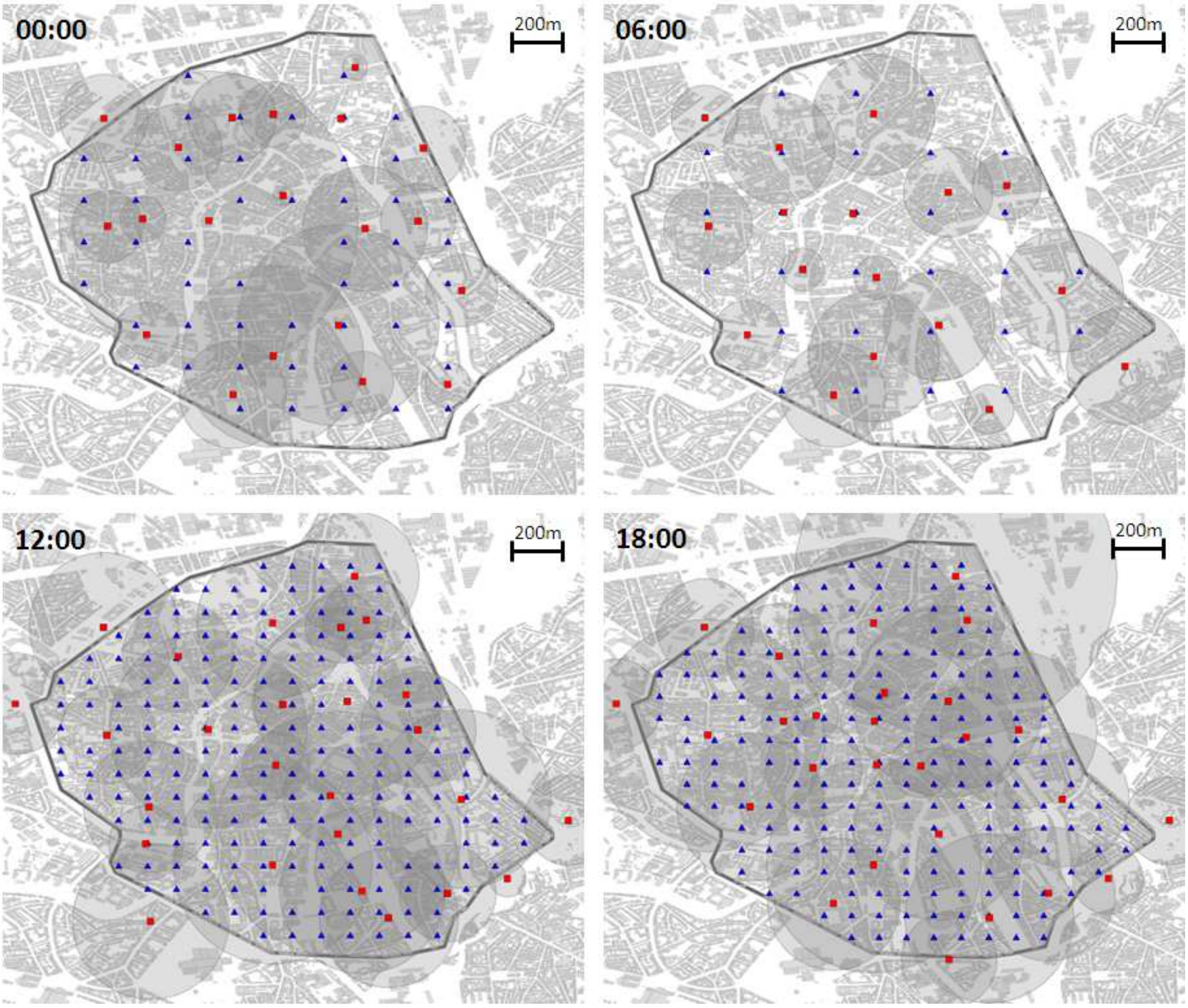

Figure 6. Overview of the network obtained by one simulation for different time intervals during the day (red square = base station location, gray circle = range of the base station, and blue triangle = user location).

Table 1. Link budget table for a macrocell and femtocell base station [*Deruyck et al.*, 2011a, b].

Parameter	**Macrocell BS**	**Femtocell BS**
Frequency [MHz]	2600	2600
Maximum input power BS antenna [dBm]	43	33
Antenna gain BS [dBi]	18	4
Antenna gain mobile station [dBi]	0	0
Soft handover gain [dB]	0	0
Feeder loss BS [dB]	0	0
Feeder loss mobile station [dB]	0	0
Fade margin [dB]	10	10
Interference margin [dB]	2	2
Receiver SNR [dB]	[-1.5, 3, 10.5, 14, 19, 23, 29.4][1]	[-1.5, 3, 10.5, 14, 19, 23, 29.4][1]
Number of used subcarriers	301	301
Number of total subcarriers	512	512
Bandwidth [MHz]	5	5
Noise figure mobile station [dB]	8	8
Implementation loss mobile station [dB]	0	0
Yearly availability	99.995%	99.995%
MIMO BS	1,4,8	1,4,8
MIMO mobile station	1,4,8	1,4,8
coverage requirement	90%	90%

(3) [1/3 QPSK, 1/2 QPSK, 2/3 QPSK, 1/2 16-QAM, 2/3 16-QAM, 4/5 16-QAM, 1/2 64-QAM, 2/3 64-QAM]

Table 2. Comparison of the power consumption and energy efficiency for the time interval 4 a.m. to 5 a.m. for the different scenarios and difference with respect to the reference scenario.

Scenario	PC p_{50}/p_{95} [kW]	σ_{PC} [kW]	CI_{PC} [kW]	EE p_{50}/p_{95} $[(km^2 \cdot Mbps)/W]$	CI_{EE} $[(km^2 \cdot Mbps)/W]$	σ_{EE} $[(km^2 \cdot Mbps)/W]$	ΔPC p_{50}/p_{95} [%]	ΔEE p_{50}/p_{95} [%]
Reference	16.2/17.2	0.6	16.2 ± 0.2	439.1/456.2	341.3 ± 29.6	114.1	—/—	—/—
CA 2x5 MHz	16.2/17.2	0.7	15.9 ± 0.2	496.7/906.4	597.0 ± 51.6	199.2	0/0	13.1/98.7
CA 3x5 MHz	16.3/17.2	0.7	16.2 ± 0.2	1302.5/1363.8	1028.0 ± 87.7	338.3	0.6/0	196.6/198.9
CA 4x5 MHz	16.2/17.2	0.8	16.0 ± 0.2	988.7/1818.5	1259.0 ± 114.1	440.1	0/0	125.2/298.6
CA 5x5 MHz	16.3/17.2	0.7	16.3 ± 0.2	2214.3/2275.2	1744.5 ± 147.7	569.8	0.6/0	404.3/398.7
MIMO 4x4	15.7/19.4	2.2	15.7 ± 0.6	342.4/379.2	340.0 ± 6.7	25.7	3.1/-12.8	-22.0/-16.9
MIMO 8x8	18.4/25.7	4.2	17.7 ± 1.1	216.8/255.0	222.2 ± 5.4	20.7	-13.5/-49.4	-50.6/-44.1
Femto	10.1/11.2	0.7	10.1 ± 0.2	336.7/755.1	471.8 ± 52.6	202.9	37.7/34.9	-23.3/65.5
Femto MIMO	5.2/5.2	0.5	4.9 ± 0.1	1396.0/1867.4	1435.6 ± 87.6	337.9	67.9/69.8	217.9/309.3
Femto CA	10.0/11.2	0.8	10.1 ± 0.2	1022.5/2044.9	1221.3 ± 134.6	519.1	38.3/34.9	132.9/348.2
Femto CA MIMO	5.2/5.2	0.6	4.8 ± 0.2	5370.1/7657.7	5852.4 ± 406.4	1567.2	67.9/69.8	1123.0/1578.6

PC = Power Consumption, σ_{PC} = standard deviation of PC, CI_{PC} = confidence interval of PC, Δ_{PC} = relative PC reduction, EE = energy efficiency, σ_{EE} = standard deviation of EE, CI_{EE} = confidence interval of EE, Δ_{EE} = relative EE gain.

Table 3. Comparison of the power consumption and energy efficiency for the time interval 5 p.m. to 6 p.m. for the different scenarios and difference with respect to the reference scenario.

Scenario	PC p_{50}/p_{95} [kW]	σ_{PC} [kW]	CI_{PC} [kW]	EE p_{50}/p_{95} $[(km^2 \cdot Mbps)/W]$	CI_{EE} $[(km^2 \cdot Mbps)/W]$	σ_{EE} $[(km^2 \cdot Mbps)/W]$	ΔPC p_{50}/p_{95} [%]	ΔEE p_{50}/p_{95} [%]
Reference	38.5/43.7	3.0	38.6 ± 0.8	13830/14130	13830 ± 52.5	202.5	—/—	—/—
CA 2x5 MHz	39.2/43.7	2.7	39.3 ± 0.7	27756/28537	27724 ± 115.8	446.5	-1.8/0	100.7/102.0
CA 3x5 MHz	38.9/43.7	2.7	38.7 ± 0.7	41590/42514	41517 ± 162.5	626.6	-1.0/0	200.7/200.9
CA 4x5 MHz	38.8/44.4	2.5	39.0 ± 0.6	55493/57004	55484 ± 245.6	947.0	-0.8/-1.6	301.3/303.4
CA 5x5 MHz	38.3/41.9	2.3	38.5 ± 0.6	69221/70626	68983 ± 279.6	1078.4	0.5/4.3	400.5/399.8
MIMO 4x4	31.7/35.7	3.1	31.8 ± 0.8	7093.4/7515.7	7061.9 ± 80.0	308.5	17.7/18.3	-48.7/-46.8
MIMO 8x8	45.9/56.0	6.1	45.9 ± 1.6	4237.0/4695.6	4228.2 ± 69.0	266.2	-19.2/-28.1	-69.3/-66.8
Femto	37.4/40.6	2.0	37.6 ± 0.5	34415/36740	34503 ± 329.6	1271.1	2.9/7.1	148.8/160.0
Femto MIMO	31.9/33.9	1.6	31.7 ± 0.4	41534/45373	41726 ± 416.2	1604.9	17.1/22.4	200.3/221.1
Femto CA	37.1/40.5	1.9	37.3 ± 0.5	119000/127060	118990 ± 1374.2	5299.6	3.6/7.3	760.4/799.2
Femto CA MIMO	32.1/34.6	1.4	32.1 ± 0.4	154340/161450	152380 ± 1578.6	6087.9	16.6/20.8	1016.0/1042.6

PC = Power Consumption, σ_{PC} = standard deviation of PC, CI_{PC} = confidence interval of PC, Δ_{PC} = relative PC reduction, EE = energy efficiency, σ_{EE} = standard deviation of EE, CI_{EE} = confidence interval of EE, Δ_{EE} = relative EE gain.

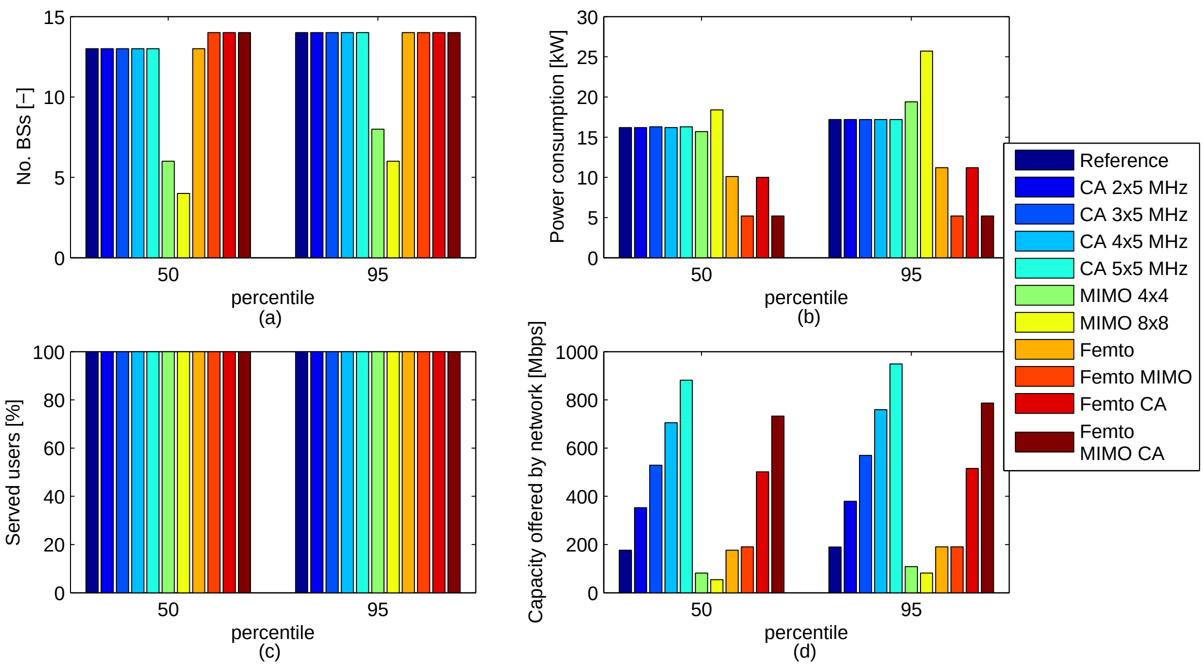

Figure 7. Comparison of different parameters (number of used base stations (a), power consumption (b), percentage of users served (c), and capacity offered by the network (d)) for the time interval 4 a.m. to 5 a.m. for the different scenarios.

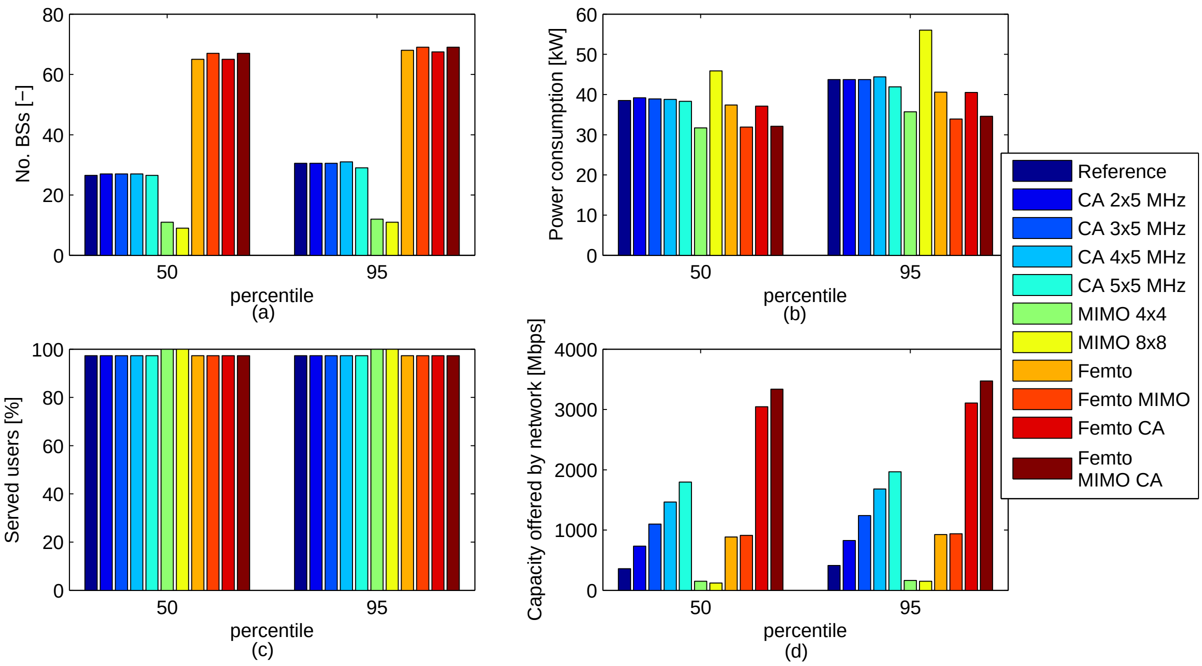

Figure 8. Comparison of different parameters (number of used base stations (a), power consumption (b), percentage of users served (c), and capacity offered by the network (d)) for the time interval 5 p.m. to 6 p.m. for the different scenarios.